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INITIAL ASSESSMENT OF THE OPERATIONAL REUSABLE BOOSTER SYSTEM (RBS) ROCKETBACK

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MARCH 2011
Interim Report

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14. ABSTRACT
The U.S. Air Force is pursuing a reusable booster system (RBS) to meet future responsive launch needs. An RBS consists of a reusable booster with and expendable upper stage. To meet operability and life cycle cost (LCC) goals, the current approach is for the RBS to return to the launch site (RTLS) after releasing the upper stage to avoid the need of operating a downrange base and avoiding the cost & time required to transport the vehicle back to the launch for the next mission. The RLTS approach discussed in this document is rocketback (sometimes referred to as boostback). This document is the first attempt to quantify the operational RBS rocketback flight envelope. Also discussed are trades on the RBS's vehicle design, specific mission scenario, and trajectory parameters that can affect the flight envelope.

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1 Introduction

The U.S. Air Force is pursuing a Reusable Booster System (RBS) to meet future responsive launch needs. An RBS is a partially reusable launch system that consists of a reusable booster with an expendable upper stage. To meet operability and Life Cycle Cost (LCC) goals, the current approach is for the RBS to Return to the Launch Site (RTLS) after releasing the upper stage to avoid the need of operating a downrange base and avoiding the cost and time required to transport the vehicle back to the launch for the next mission. The RLTS approach discussed in this document is rocketback (sometimes referred to as "boostback").

This document is the first attempt to quantify the operational RBS rocketback flight envelope. Also discussed are variations on the RBS's vehicle design, specific mission scenario, and trajectory parameters that can affect the flight envelope.

The information presented here is the opinion of the authors based on an initial survey and study of various approaches to the rocketback maneuver. Also discussed are the needs further study and refinement.

There are many existing published technical papers that the reader is encouraged to review along with this document[1,2,3,4].

2 Background

2.1 Assumptions

The following assumptions are used in this document:

- The operational RBS has a reusable first stage and expendable upper stages
- The booster stage's propellant combination is Liquid Oxygen (LOX) and Kerosene
- The entire system lifts off vertically. The RBS lands horizontally on a runway in the vicinity of the launch pad using fixed wings.
- The rocket engines used to execute the rocketback trajectory are located on the aft end of the vehicle (see Figure 16).

2.2 Traditional Airplane and Launch Vehicle Flight Envelopes

Aircraft, launch vehicles, and spacecraft are subject to various physical and practical limitations in their operation. An important tool for quantifying these limitations is the flight envelope diagram. The purpose of this section is to introduce several examples of flight envelope diagrams to place the reader in the proper mindset for considering the flight envelope of the RBS.

2.2.1 Airplane V-n Diagram

A common flight envelope defined for an aircraft is the V-n diagram (see Figure 1). The V-n diagram illustrates both the aerodynamic and structural limitations of a particular aircraft. The curved boundaries in this flight envelope are defined by the aircraft's maximum lift coefficient (C_{Lmax}) performance at various flight velocities. Beyond C_{Lmax}, the aircraft will stall, and the magnitude of the load factor will decrease until it is once again within the envelope. The straight line boundaries on a V-n diagram are defined by structural load limits. The upper and lower load factor limits are based on the maximum positive and negative lift forces that the aircraft can withstand. Finally, the vertical boundary on the righthand side, the *Never Exceed Speed*, is defined by the maximum dynamic pressure that the airframe will accommodate. While the traditional V-n diagram is useful for unpowered glide, this document presents different approaches to quantify and visualize other portions of the rocketback flight envelope.

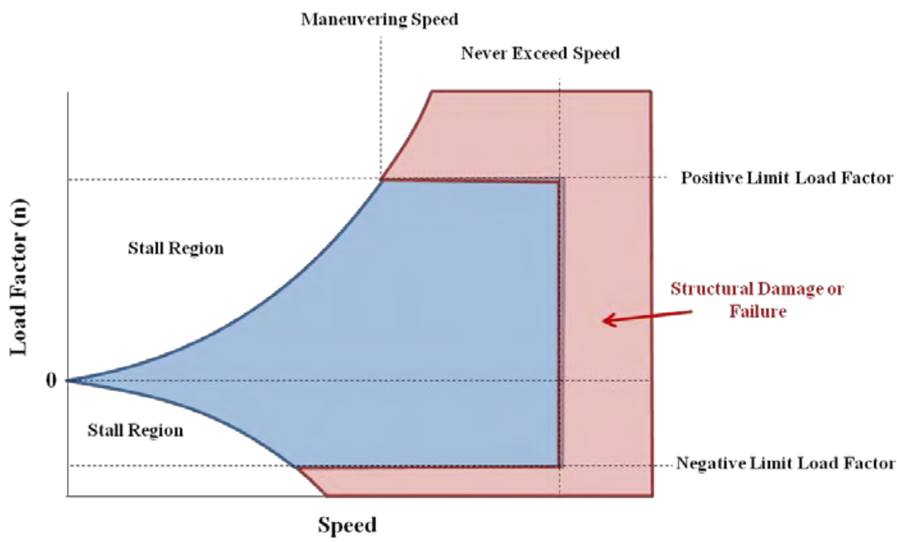


Figure 1. Traditional Airplane V-n Diagram (Maneuver-Gust Diagram)

2.2.2 Flight Envelope of Rocket Powered Space Access Vehicles

2.2.2.1 Ascent Corridor

The first part of the RBS's flight is ascent. Figure 2 and Figure 3 illustrates a notional ascent corridor for an RBS, from launch to the booster staging point. In this case, the upper boundary of the envelope is determined by the requirement to transition from vertical velocity to horizontal velocity in order to attain orbit. A launch vehicle that does not "turn" sufficiently will either fail to enter orbit or do so very inefficiently. The lower boundary is governed by aerodynamic loads. In particular, if a launch vehicle does not climb sufficiently in proportion to its flight velocity, then the dynamic pressure, and therefore drag force, will be excessively high.

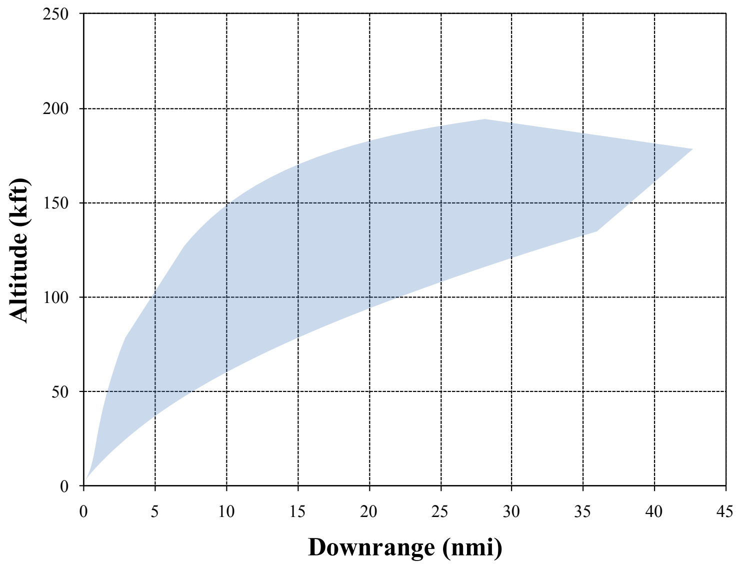


Figure 2. Notional RBS Ascent Corridor

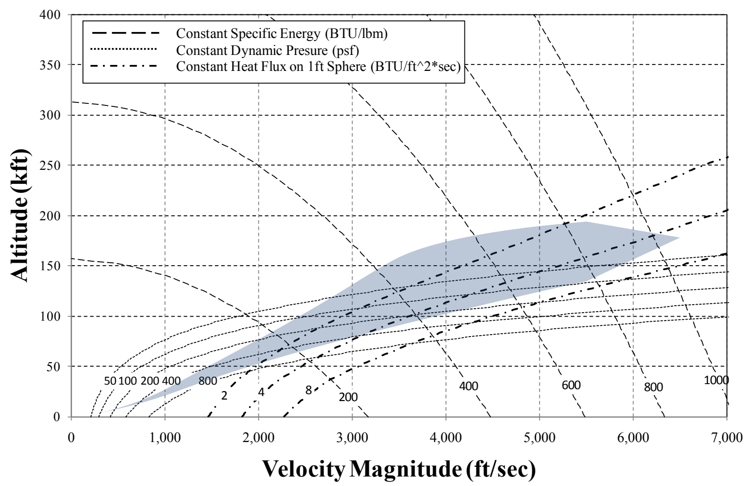


Figure 3. Notional RBS Ascent Corridor

2.2.2.2 Space Shuttle Re-Entry (STS-1)[5]

For comparison purposes, the re-entry trajectory of the Space Shuttle Orbiter from its first flight (STS-1) and a sample RTLS abort trajectory (which has never been flown) are presented in Figure 4 and Figure 5 shown in similar manners to which the rocketback flight envelope will be presented. The re-entry trajectory glide is increasing the dynamic pressure and lowering the angle of attack (until reaching subsonic speeds).

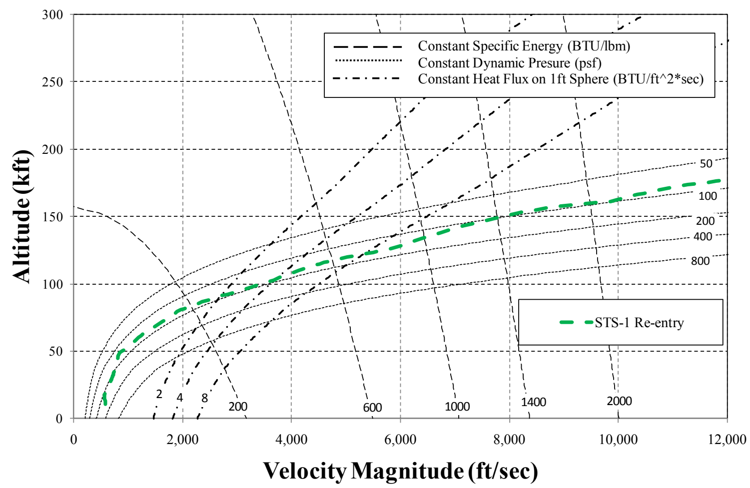


Figure 4. Space Shuttle STS-1 Re-Entry

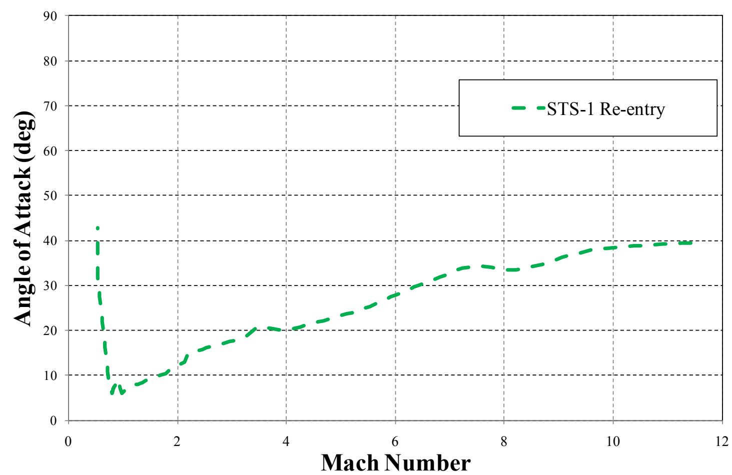


Figure 5. Space Shuttle STS-1 Re-Entry

2.3 Rocketback Trajectory Attributes

This section is meant to provide an initial set of definitions for use in studies and efforts that include the rocketback maneuver for an RBS. These definitions are not intended to discuss which attributes are more optimal or beneficial to an RBS.

Rocketback Trajectory – Refers to an RBS post staging event RTLS trajectory that utilizes on-board rocket propulsion to produce the necessary acceleration to bring the RBS back for recovery within the vicinity of the launch site.

2.3.1 Components of the Rocketback Trajectory

Post-Staging – The RBS has separated from the upper stage. The RBS is maneuvering to keep from colliding with the upper stage but is not yet trying to produce acceleration to bring the RBS back for recovery within the vicinity of the launch site. This portion of the rocketback trajectory can include flying with the engine on or engine off.

Orienting the Vehicle – The maneuvers to position the vehicle where the rocket propulsion system can begin to produce the necessary acceleration to bring the RBS back for recovery with in the vicinity of the launch site. This can be done with the rocket propulsion on or off. If the orientation of the vehicle is done with the propulsion off, then an in-flight restart of the engine is necessary. For the downrange type of rocketback trajectory (see 2.3.2 below), the vehicle will re-enter before the vehicle is properly oriented. This portion of the rocketback trajectory can include flying with the engine on or engine off.

Rocketback Burn – The period of time where rocket propulsion system is producing the necessary acceleration to bring the RBS back for recovery within the vicinity of the launch site

Rocket Engine Cut-Off (RECO) – The point in time where the rocket propulsion system is turned off and the vehicle has enough energy to be recovered in the vicinity of the launch site using only aerodynamic forces.

Re-Entry – The RBS is descending and will undergo significant aerodynamic force but the vehicle will not be able to glide in equilibrium.

Achieve equilibrium glide – This is the point in time where the aerodynamic forces on the RBS are in balance to allow for a constant glide slope and the vehicle has enough energy to land in the vicinity of the launch site without the use of any more propulsive force.

2.3.2 Types of Rocketback

In-Plane – During this maneuver, the vehicle's velocity vector is rotated vertically (either toward-the-sky or toward-the-ground) in the plane of the velocity vector at staging. Most of the turning is achieved by using rocket thrust vectoring (main engine and/or reaction control system (RCS) thrusters) and gravitational forces. This maneuver results in the vehicle starting its reentry and descent in the opposite horizontal direction which it was traveling at staging. Two sub-variants of the maneuver can be defined based on whether the rocket engine is on or off during the post-separation reorientation maneuver.

Out-of-Plane – This maneuver results in the vehicle starting its reentry and descent in a direction that is not effectively opposite to the direction in which it was traveling at staging.

Partial – This maneuver involves using rocket thrust to just slow the downrange travel of the vehicle. The vehicle continues downrange during re-entry. It then performs a glideback aerodynamic turn, descent, approach and landing from the RECO point.

Downrange – This maneuver is significantly different from the other three rocketback variants. During this maneuver, the vehicle's engine is shutoff at the staging point. It then re-enters, continuing is downrange travel. Following re-entry, the vehicle performs a predominately aerodynamic turn until the velocity vector is pointed towards the landing site and then fires one or more rocket engine. The rocket engine continues to accelerate the vehicle towards the landing site until RECO. From there, an unpowered re-entry, descent, approach, and landing is performed.

2.3.3 Trajectory Characteristics

2.3.3.1 Flight Path

This section discusses two different characteristics of the rocketback trajectory when it is plotted on an altitude vs. downrange plot. Section 5.4 below has illustrations and more discussion about this trajectory characteristic. These variations in flight path don't apply to a partial or downrange type of rocketback trajectory.

Over the Top – After staging, the rocketback trajectory loops towards the sky and the vehicle will go through a positive 90 degree flight path angle before RECO.

Underneath – After staging, the rocketback trajectory loops towards the ground and the vehicle will go through a negative 90 degree flight path angle before RECO.

2.3.3.2 Vehicle Rotation Direction

This section discusses the direction in which the vehicle is rotated during the rocketback maneuver so as to orient the booster's rocket engines of the vehicle to provide the necessary acceleration for the RTLS maneuver. A RBS trajectory may be a combination of nose up turning and sideways turning or nose down turning and sideways turning. A diagram of these definitions is shown in Figure 6. These variations in vehicle rotation direction don't apply to a downrange type of rocketback trajectory.

Nose up turn – After staging, the vehicle rotates upward so at some instant its nose is pointed towards the sky. This rotation is in the plane of the vehicle's velocity vector at the beginning of orienting the vehicle and is about the pitch Euler angle[6].

Nose down turn – After staging, the vehicle rotates downward so at some instant its nose it point towards the Earth's surface. This rotation is in the plane of the vehicle vector at the beginning of orienting the vehicle and about the pitch Euler angle[6].

Sideways turn – The vehicle is rotated left or right in the plane parallel to the local Earth' surface This rotation is about the yaw Euler angle[6].

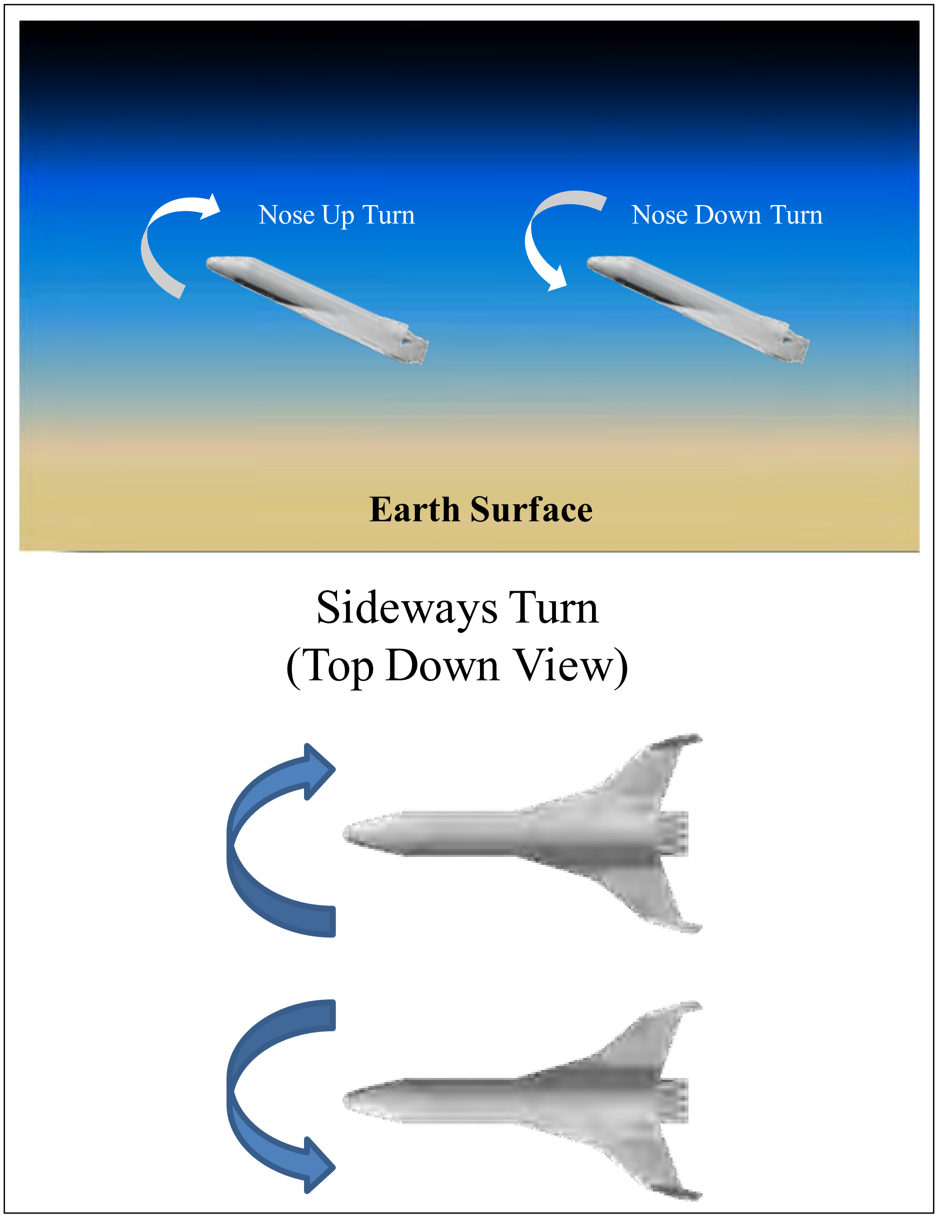


Figure 6. Diagram of Vehicle Rotation Direction Rocketback Trajectory Characteristic

2.3.3.3 Orientation at Staging

This section discusses the direction in which the vehicle is oriented at the staging point before beginning the rocketback maneuver. An orientation of the RBS at staging may be a combination of Heads Up and Sideways or Heads Down and Sideways. A diagram of these definitions is shown in Figure 7.

Heads Up – The re-entry windward surface of the RBS is facing the ground at staging.

Heads Down – The re-entry leeward surface of the RBS is facing the ground at staging.

Sideways – The re-entry windward is oriented perpendicularly to the ground at staging.

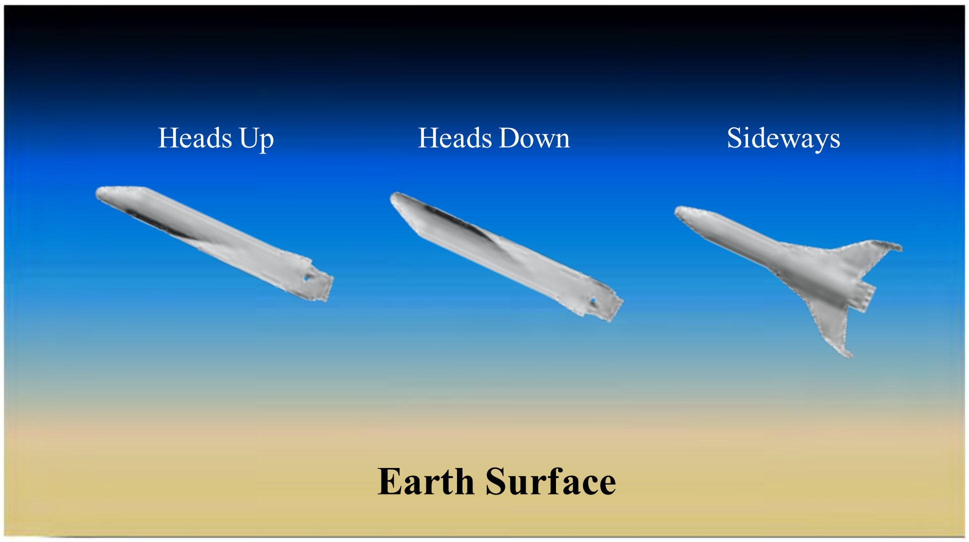


Figure 7. Diagram of Orientation at Staging Rocketback Trajectory Characteristic

3 Initial Rocketback Flight Envelope

This section presents the authors' current understanding of the operational RBS rocketback flight envelope. The charts in this section are meant to be a starting point for future efforts to further define and understand these envelopes. The plots below are just some of the ways in which the envelope can be visualized. Other methods of visualizing the envelope need to be studied and considered.

The data used to generate these plots comes from a variety of RBS operational vision vehicle concepts (all are designed for rocketback) and approaches to modeling the rocketback trajectory. Vehicle differences include outer mold line shapes, upper stage assumptions (number of stages, propellant choice, material choices, engine selection, etc.), engine assumptions (gimbal angles, number of engines, performance, etc.), payload capabilities, staging point flight conditions (speed, altitude, and flight path angle, etc.), launch site locations, launch inclinations, and booster stage mass fractions. Trajectory modeling differences include tool use (such as POST[6] or OTIS[7]), rotation dynamics, orientation of the vehicle at staging, engine throttling levels, vehicle rotation direction, and optimization scheme.

3.1 Altitude vs. Velocity

The example of an operational RBS rocketback envelope is presented here plotted as a graph of altitude vs. velocity (magnitude relative to the Earth's surface). The envelope is broken up into the portion of the flight from the staging point to RECO (Figure 8) and RECO to achieving equilibrium glide (Figure 9). The envelope in Figure 8 includes post-staging, orienting the vehicle, rocketback burn portions, and RECO components of the rocketback trajectory. The envelope in Figure 9 includes the re-entry and achieves equilibrium glide portions of the rocketback trajectory.

For comparison purposes, all flights of the X-15[8] and the re-entry path of the Space Shuttle orbiter from the STS-1 flight[5] are plotted with the flight envelope. This was included since these two vehicles are sometimes used as comparisons to the RBS, but the graphs below show they have very different trajectories than rocketback.

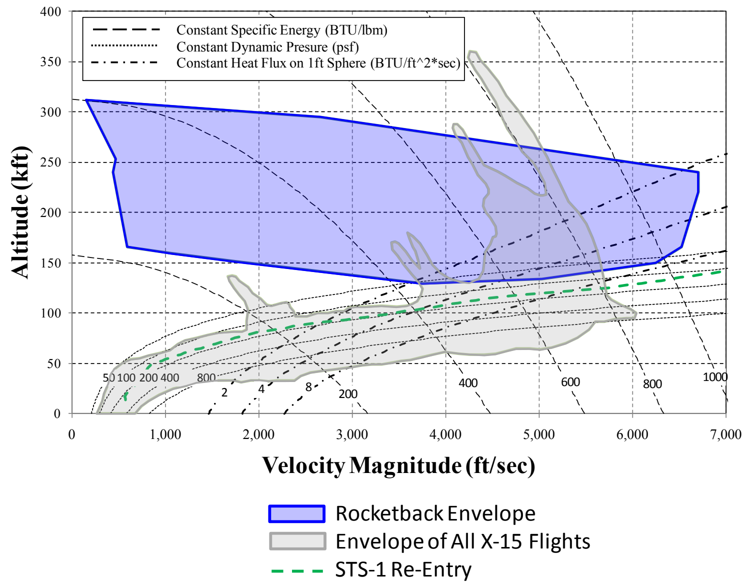


Figure 8. Rocketback Flight Envelope from Staging Point to RECO, Plotted as Altitude vs. Velocity

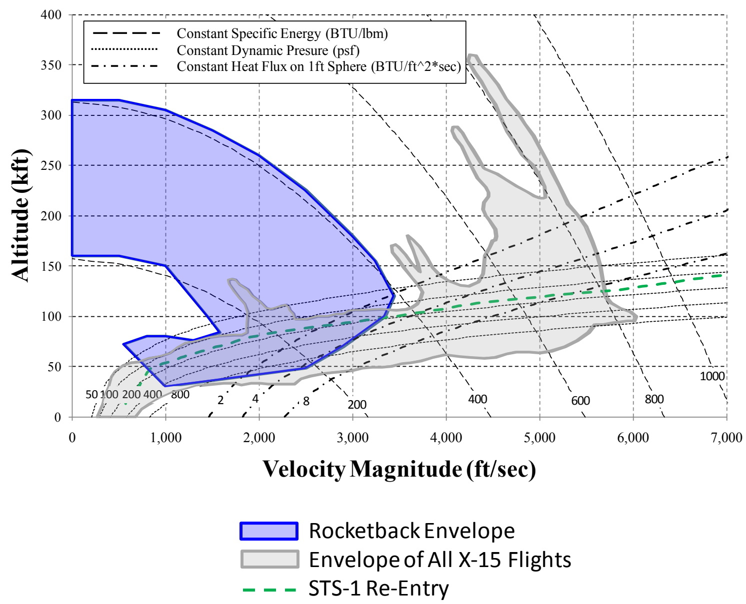


Figure 9. Rocketback Flight Envelope from RECO to Equilibrium Glide, Plotted as Altitude vs. Velocity

3.2 Angle of Attack vs. Mach Number

The operational rocketback flight envelope presented here shows angle of attack vs. Mach number where there is significant aerodynamic force on the vehicle from the staging point until RECO. An example rocketback trajectory of it plotted this way is shown in Figure 10 where the angle of attack is plotted vs. Mach number with the change dynamic pressure. Analyzing the various operational RBS rocketback trajectories used to develop this flight envelope resulted in Figure 11. Regions where the dynamic pressure is below 2psf are not included.

The flight envelope during re-entry where dynamic pressure is above 20psf is shown in Figure 12 and is compared to the X-15's demonstrated Mach ~1+ envelope and the STS-1 re-entry.

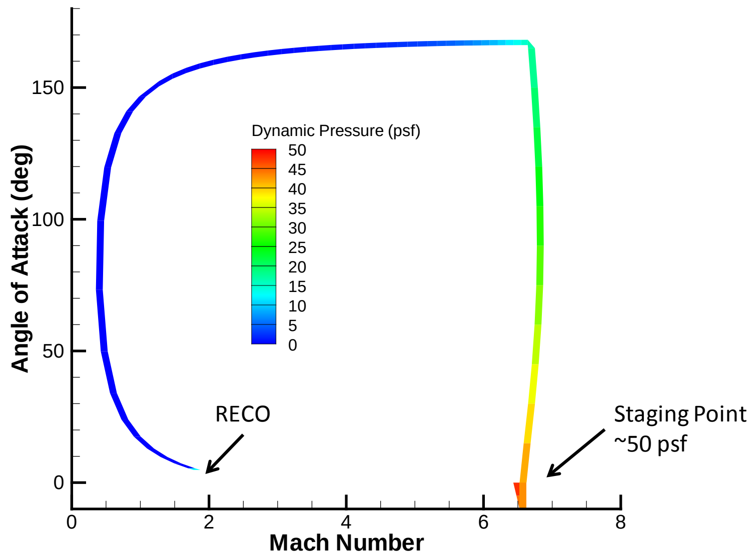


Figure 10. Sample Trajectory from Staging Point to RECO

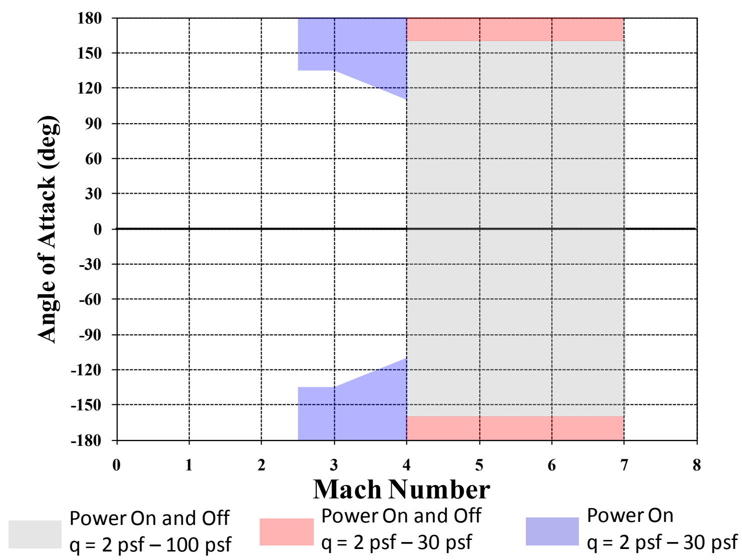


Figure 11. Rocketback Flight Envelope from Staging Point to RECO with Dynamic Pressure above 2 psf, Plotted as Angle of Attack vs. Mach Number (only plotting |α| ≥ 30º)

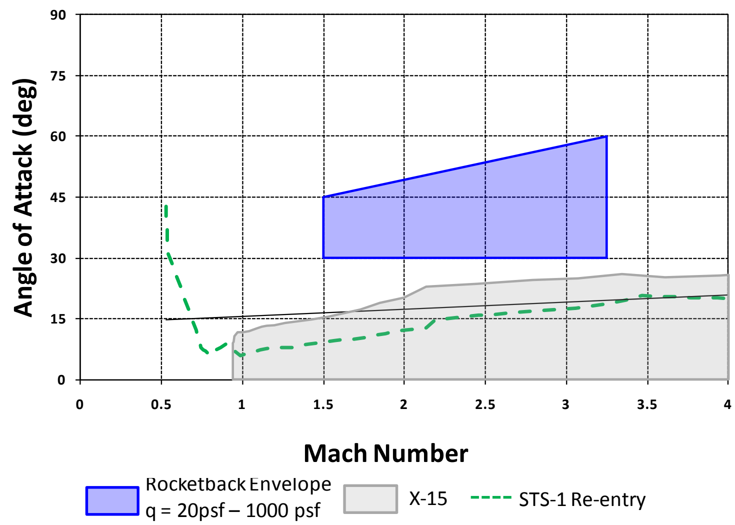


Figure 12. Rocketback Flight Envelope from RECO to Equilibrium Glide with Dynamic Pressure above 20 psf, Plotted as Angle of Attack vs. Mach Number (only plotting |α| ≥ 30º)

3.3 Reynolds Numbers vs. Mach Number

The operational rocketback flight envelope is presented here with Reynolds number vs. Mach number for various ranges of angles of attack. The length scale used is a 100 ft as this represents a nearly average length for a typical operational RBS vehicles design.

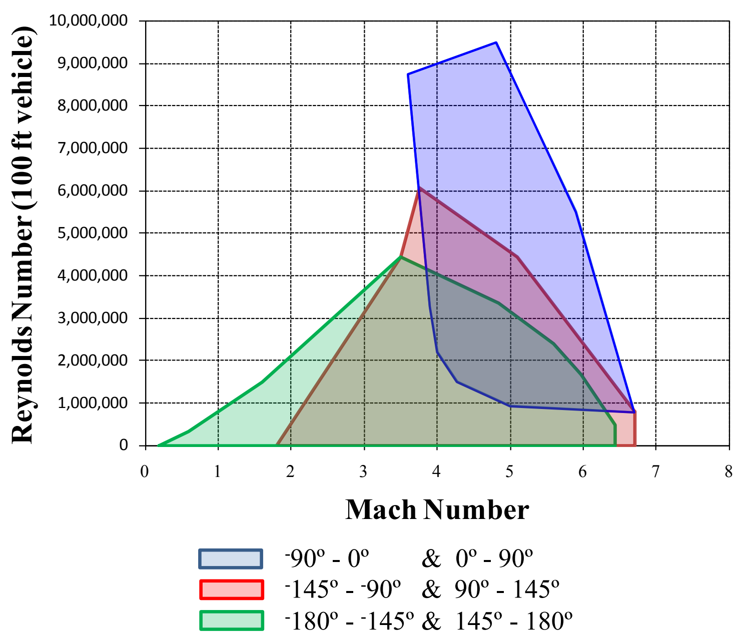


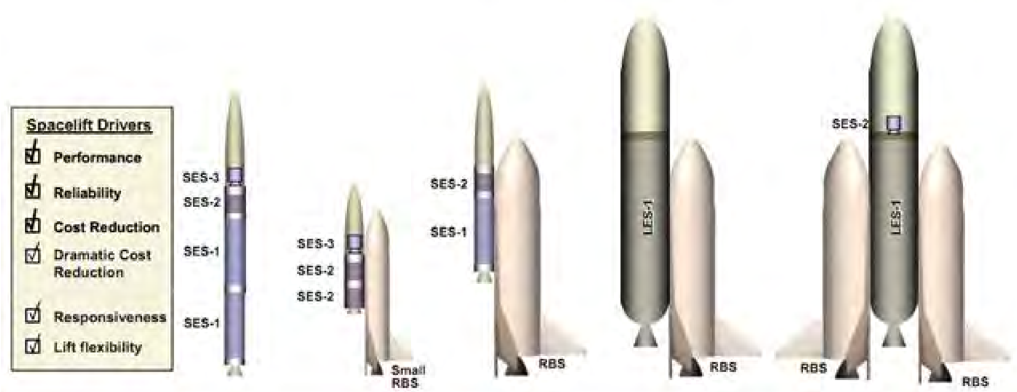
Figure 13. Rocketback Flight Envelope from Staging Point to RECO, Plotted as Reynolds Number (assuming a 100 ft long vehicle) vs. Mach Number

4 Vision Vehicle Tradespace Options

This section presents some of the trades on a RBS vision vehicle that can have an impact over which parts of the rocketback flight envelope an RBS will fly for a particular mission. Some of these trades include how a particular vehicle design can be utilized to fit different missions and may have an impact on the rocketback flight envelope.

4.1 A Family of RBS Vehicles

As presented in the Space and Missile Center Spacelift Development Plan[9], the Air Force is considering a family of potential RBS configurations (see Figure 14). These vehicles range from a small RBS designed to lift a payload of approximately 5,000 lbs to due Low Earth Orbit (LEO), to a larger system that delivers 20,000 lbs, to a heavy lift configuration that may use two RBS vehicles along with other expendable stages to deliver in excess of 60,000 lbs of payload.



	Small	Small	Med-Lite	Medium	Heavy
Lb to LEO	5,000	5,000	16,500	50,000	64,000
Cost savings	0	~33%	~50%	~50%	~50%
Approx IOC	2015-2020	2019	2025	2025	2030

SES = Small Expendable Stage, LES = Large Expendable Stage

Figure 14. Notional Family of RBS Vehicles

It is likely that each of these configurations will require a different adaptation of the rocketback maneuver due to differing staging conditions (velocity, flight path angle, etc.).

4.2 Variation of Payload Delivered by a Particular RBS Design

It is conceivable that a particular RBS vehicle will be required to fly missions with various payload sizes. For example, a vehicle designed to carry 20,000 lbs to a particular low earth orbit may occasionally be required to deliver a 15,000 lb or even 10,000 lb payload. In this case, for example, a RBS ascent trajectory with less payload may differ from that of a maximum payload mission. It is therefore possible that the initial conditions for the rocketback maneuver may differ from the nominal mission in such cases.

4.3 Variation of Upper Stage Size or Type

In some cases, the RBS may also be required to carry a modified or fundamentally different upper stage system. For example, although a nominal upper stage system may be a two-stage liquid propellant system, there may be a class of missions that can be flown using only one of the two upper stages. In another potential scenario, a multi-stage solid propellant upper stage could be substituted for the nominal liquid upper stage for certain missions.

In either of the above cases, for example, a RBS ascent trajectory may differ with varying upper stages in terms of accelerations, loads, and other flight parameters. By extension, the rocketback maneuver in these cases may be initiated from different staging points.

4.4 Achieving Various Orbital Inclinations

The future RBS may be required to deliver payloads to a variety of orbital inclinations. Such flexibility may be achieved by a combination of multiple launch sites located at different latitudes, and the use of dog leg trajectories that insert the payload into something other than a due East orbit (see Figure 15). These alternative ascent and RTLS trajectories will likely influence the rocketback flight envelope.

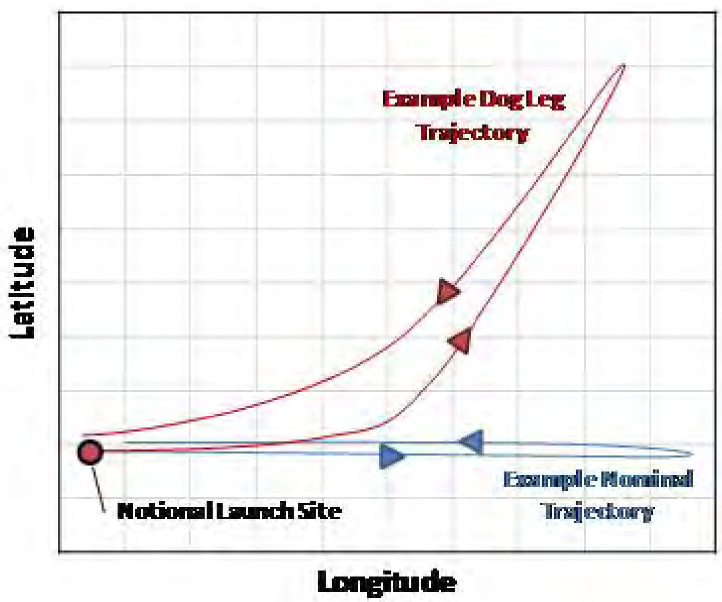


Figure 15. Example illustration of dog leg trajectory

4.5 Aborts

It may be feasible to execute an intact abort from certain in-flight failures. In the event of an abort, the RBS vehicle may execute a rocketback, partial rocketback, aerodynamic turn, or other maneuver to safely return to the launch site. Such a maneuver may involve flying in a different and potentially more stressing flight environment than would be experienced during a nominal ascent. Knowledge and understanding of any potential abort conditions is relevant to establishing the RBS rocketback flight envelope.

5 Rocketback Trajectory Parametric Trades

This section presents a brief discussion of a study recently conducted, which attempted to parameterize the rocketback trajectory for an operational RBS. The study looking at various rocketback RTLS maneuvers based on a single RBS vision vehicle concept. The RBS concept assumed for this study was a partially-reusable vehicle with a winged-body booster mated to an expendable upperstage sized to deliver 20Klbs to LEO from CCAFS (Figure 16). The booster is capable of RTLS accomplished via a rocket-powered boost back maneuver. Detailed results for this study will be published in an upcoming AFRL technical report published under this project work unit number (see standard form 298 above).

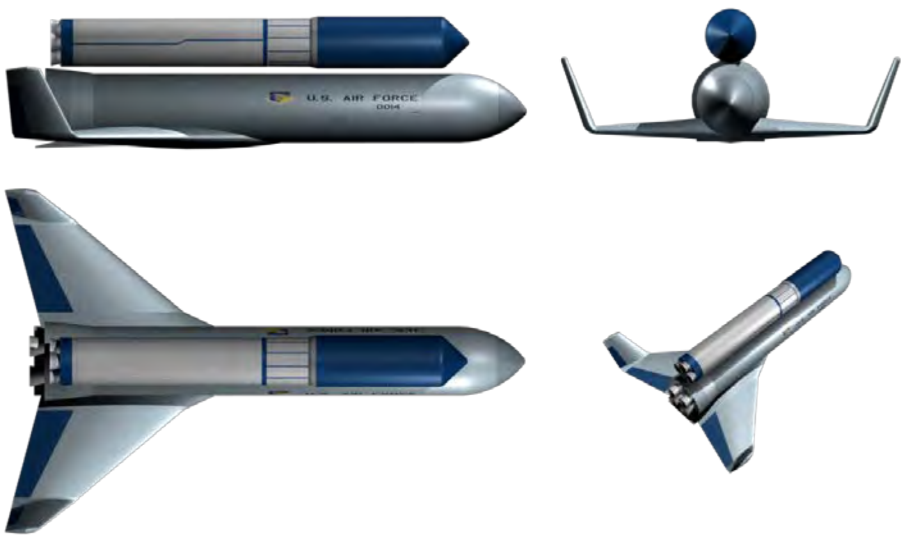


Figure 16. Reference RBS Vision Vehicle Concept

5.1 Study Focus

This study focused on conducting single design variable sensitivity studies to determine how these vehicle or trajectory values affect the overall RBS vehicle solution. Over 160 concept closure/point-designs were performed for 13 different trajectory and vehicle parameters for 3 different rocketback trajectory methods. For each case, approximately 100 different parameters of interest were tracked (e.g. mass ratio, dry weight, maximum Gs, flight time, etc.). Additionally, a comparison of over the top versus underneath RTLS trajectories was conducted.

5.2 RTLS Maneuvers

For each single variable sensitivity sweep three different types of rocketback maneuvers where performed. These three maneuvers differed in how the booster rotated after staging to begin the RTLS trajectory. The different rotation maneuvers studied were in-plane pitch, pure yaw turn, and a coordinated bank – pitch. Figure 17 - Figure 19 graphically show the three rotation types. For the in-plane pitch the booster rotates purely around the pitch axis, while for the pure yaw the booster is assumed to rotate only about the yaw axis. During the coordinated bank – pitch maneuver the booster both rotates around the pitch axis while rolling. It should be noted that for all three maneuvers it was assumed that the main rocket engines of the booster were responsible for rotating the vehicle. Also, nominal staging is occurring at a dynamic pressure of 20 psf so aerodynamic forces of the booster during the maneuvers are very low. Results from this study showed that the particular RTLS rocketback rotation technique had little influence on top-level vehicle performance and sizing. For each single variable sweep, similar trends and required RTLS delta-Vs were obtained for each of the three rotation maneuvers. While the RTLS rotation maneuvers seem equivalent from a simple vehicle performance standpoint other discriminators like controllability, RCS requirements, rocket engine plume interaction, may cause one maneuver type to be favored.

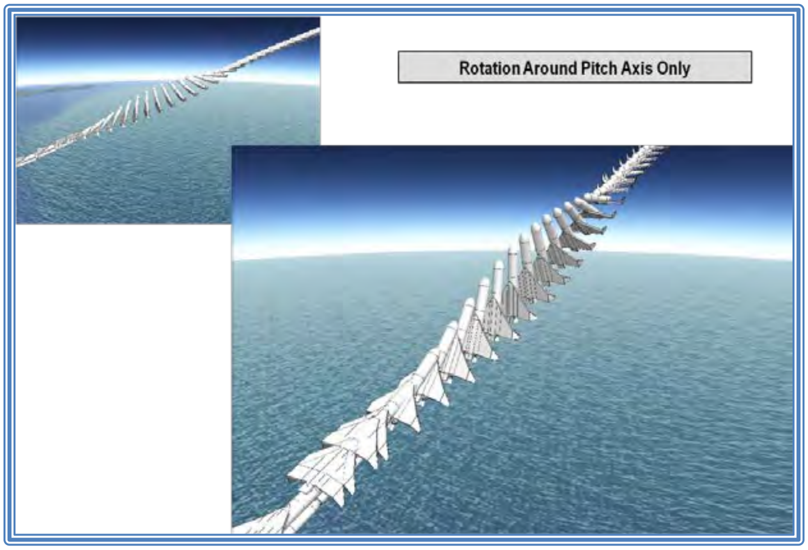


Figure 17. In-Plane Pure Pitch Turn.

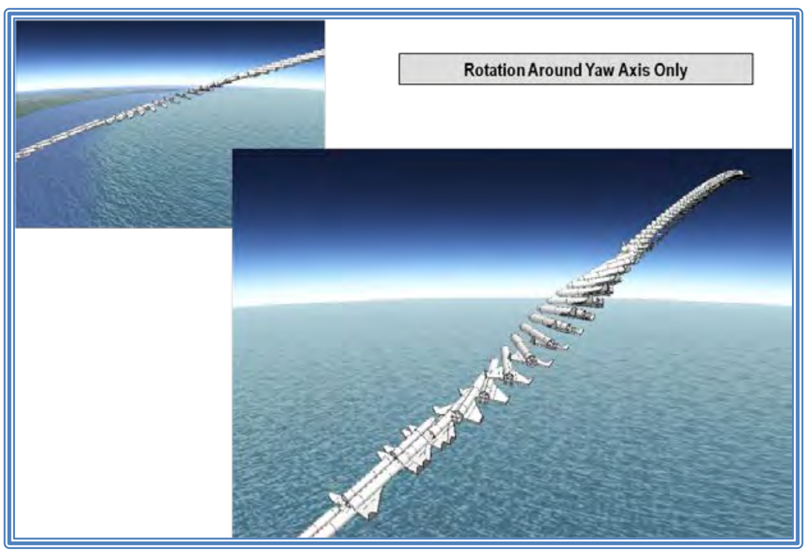


Figure 18. Pure Yaw Turn

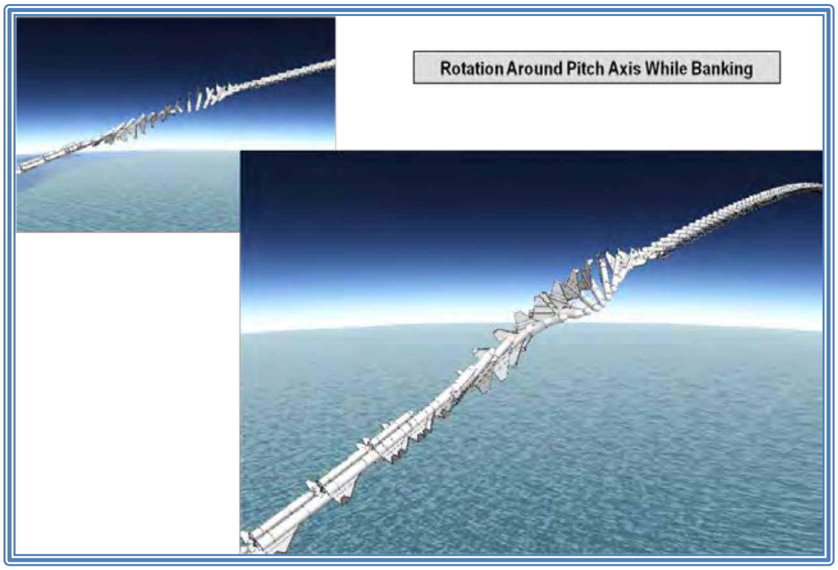


Figure 19. Coordinated Bank - Pitch Turn

5.3 Single Variable Trade Studies

As mentioned previously, 13 different single variable trade studies were conducted to determine the effect of these variables on the overall RBS vehicle closure results. For each trade study, all design variables were set to their baseline settings, expect for the single variable being studied, which was varied over a range of settings. For each specific variable setting the RBS vehicle design was re-closed to determine to effect of changing a specific design parameter. Table lists the 13 design variables that were studied along with their baseline settings and the settings used during the single variable trades.

Table 1. Single Variable Trade Design Variables.

	Baseline Setting	Setting - 1	Setting - 2	Setting - 3	Setting - 4	Setting - 5
Liftoff T/W	1.20	1.15	1.25	1.35	1.45	
Maximum Normal Gs	-2.5	-2.0	-3.0	-3.5		
Booster Lift Multiplier	1.0	0.75	1.25	1.5		
Staging Velocity (fps)	5,500	4,500	5,000	6,000	6,500	
Staging Flight Path Angle (deg)	20	10	15	25	30	35
Staging Dynamic Pressure (psf)	25	10	50	100		
Booster Engine Isp (seconds)	Baseline + 0 seconds	Baseline - 10 seconds	Baseline - 5 seconds	Baseline + 5 seconds	Baseline + 10 seconds	
Booster Engine Throttle (%)	40%	30%	60%	80%	100%	
Booster Engine Throttle During Rotation Only (%)	40%	0%	20%	60%	80%	100%
Booster RTLS Rotation Rate (deg/s)	12	8	15			
Time Delay to Initiate RTLS Maneuvers (sec)	1	0	2	3	4	5
Booster Initial Reentry AOA (deg)	38.1	25.0	35.0	45.0		
Final Booster Alt. upon Return over Launch Site (ft)	15,000	10,000	20,000	25,000	30,000	

Results from the single variable sensitivity study may help to provide guidance for future designers of RBS vehicles. For some variables, settings that may produce minimal weight solutions were identified. Other trades showed clear trends in resultant vehicle performance, as vehicle and trajectory design parameters were varied. The vehicle staging velocity appears to be the single largest driver on the system size and weight. The low staging flight path angles and low staging dynamic pressures were the next strongest drivers on system weight. Minimal impact to the system sizing was seen when the initial angle-of-attack at reentry or when the final altitude trades were conducted. It should be noted that not all of the input variables swept during this study were parameters that future RBS vehicle designers will be able to control directly. However, even sensitivities to these variables, which are not directly set by RBS vehicle designers, can help inform the designers of the impact these variables may have if their values do change from their assumed nominals.

5.4 "Over the Top" versus "Underneath" RTLS

For in-plane pitch rocketback RTLS trajectories, two different general types of flight paths have been observed across multiple studies. The first type is an "Over the top" trajectory, where the vehicle's flight path angle passes through +90 degrees during RTLS. The second type is an "Underneath" trajectory where vehicle's flight path angle passes through -90 degrees during RTLS. A survey of various independently done rocketback simulations (developed outside of this study) show that ~75% of these go over the top. However, during the rocketback parametric study outlined in the previous section, most of the simulations were underneath trajectories. Representative over the top and underneath simulations are presented in Figure 20 and Figure 21.

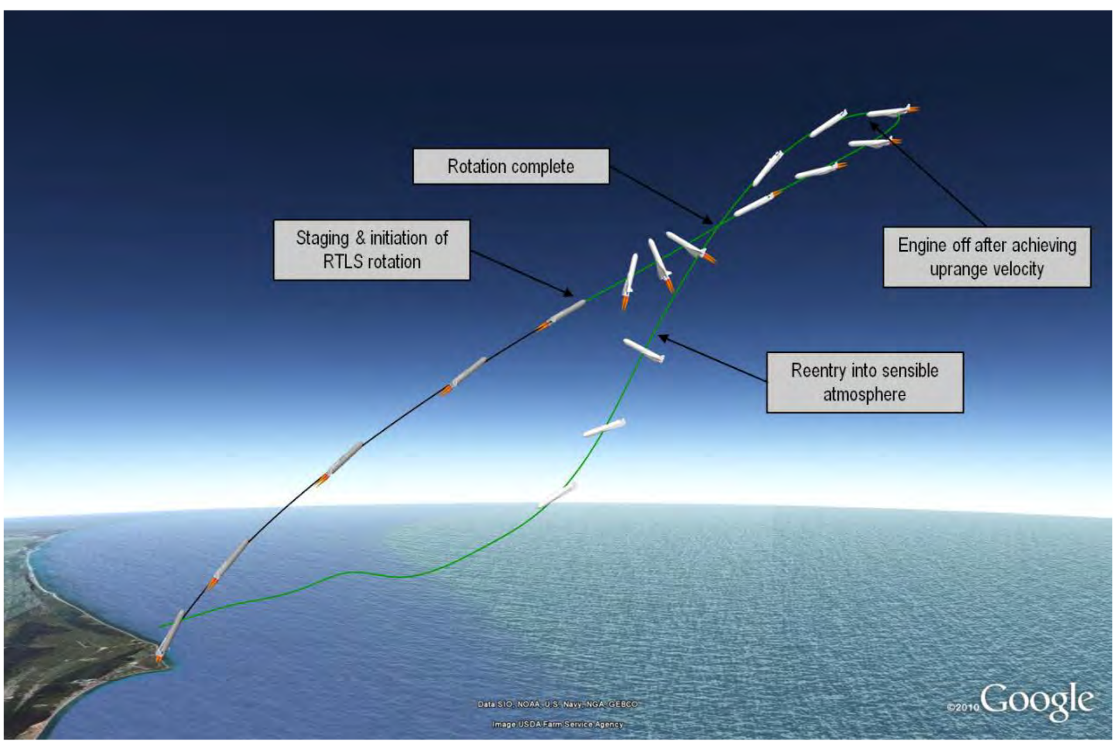


Figure 20. "Over the Top" RTLS Trajectory

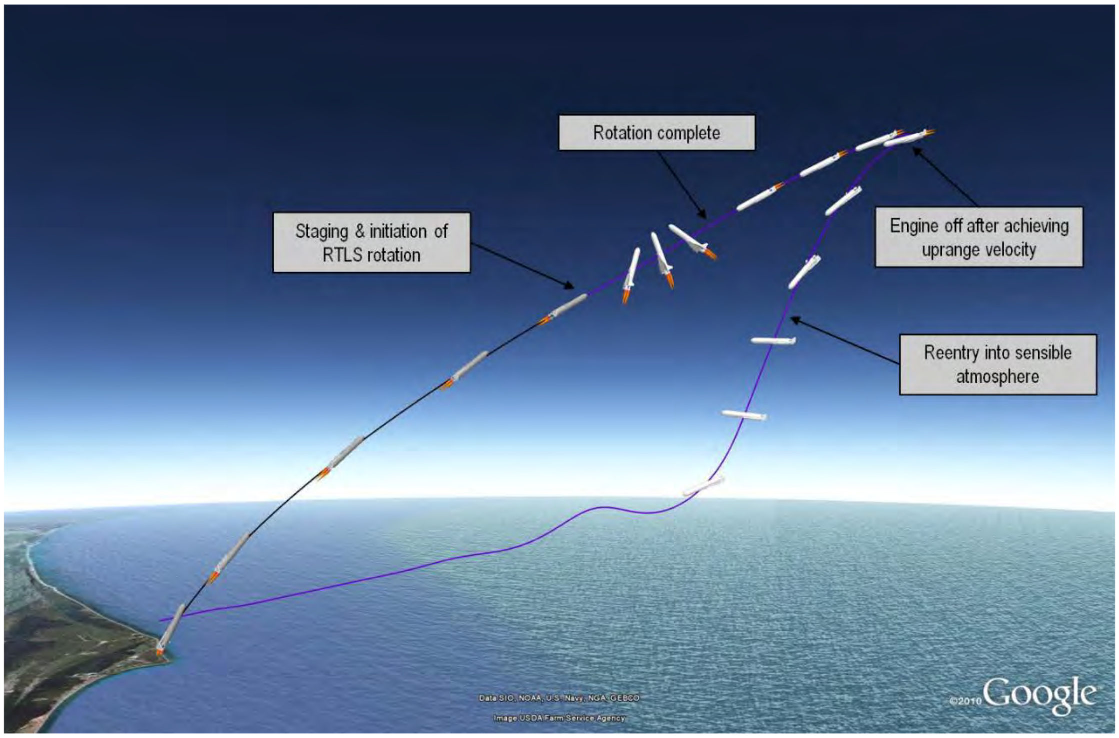


Figure 21. "Underneath" RTLS Trajectory

As part of the rocketback parametric study outlined previously, both over the top and underneath RTLS simulations starting from the same staging conditions were investigated. The performance results and the behavior of the optimization process for each simulation type were compared. For this study, booster staging conditions and vehicle design parameters were chosen that were representative of those seen for a typical over the top simulation. In general, it was difficult achieve an over the top simulation starting from a typical underneath trajectory simulation solution. The underneath simulation had to be forced to go over the top by imposing constraints to make the flight path angle go through +90 degrees. After forcing an over the top trajectory, the constraints imposing that flight path were removed and the simulation continued to go through a flight path angle of +90 degrees. This behavior implies there may be two regions in the design space where local minimum exist - one for over the top and one for underneath flight paths. Figure 22 overlays an over the top and underneath RTLS trajectory for comparison.

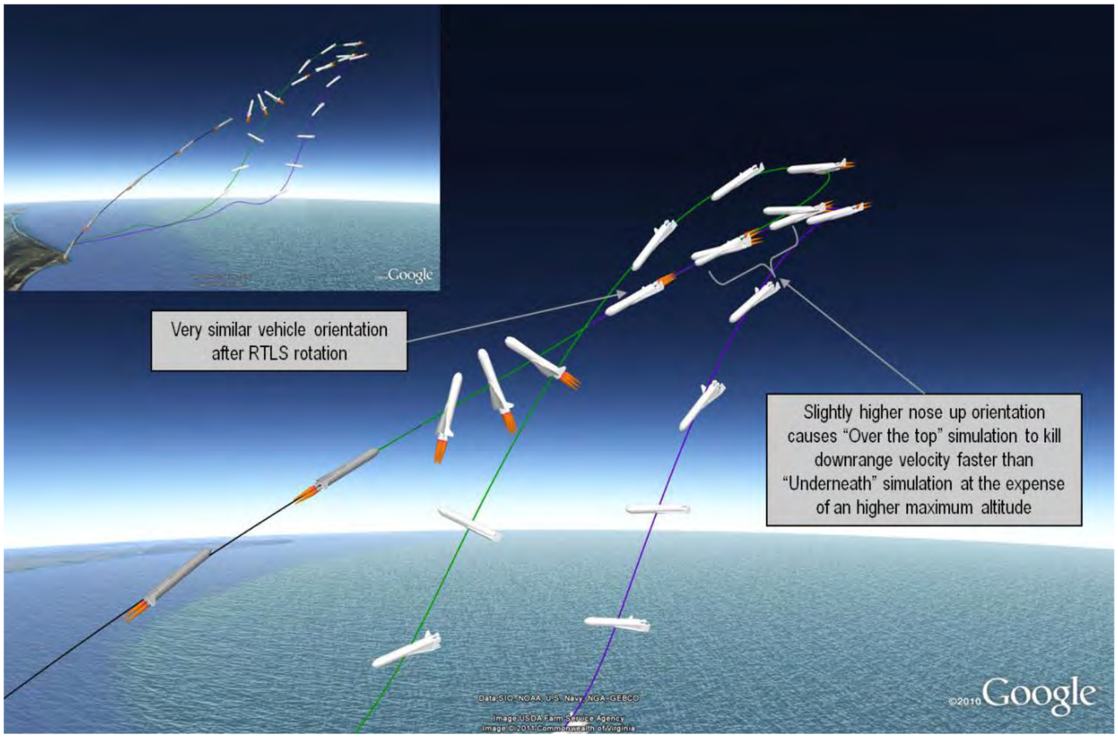


Figure 22. "Over the Top" and "Underneath" RTLS Trajectories

For this particular study, the underneath simulation was slightly better than the over the top simulation from a pure performance standpoint. For the over the top rocketback trajectory the RTLS mass ratio was 1.895, compared to an RTLS mass ratio of 1.870 for the underneath simulation. This analysis was not part of the scope for the original parametric study outlined in Section 5.1 and was conducted near the end of the task as an add-on activity. Therefore, this issue wasn't studied in great detail and warrants further investigation to answer the many questions that still surround this RTLS trajectory variation. Some of these questions include – Is the performance benefit seen for underneath trajectories only valid for certain design choices? How dependent are the results on the aerodynamic values used in the simulation? If other analysts who typically see over the top trajectories forced their simulations underneath would they see a performance advantage? Are there other non-performance reasons to prefer one option over the other?

6 Conclusions

The data and discussion presented are the authors' first attempt to visualize and quantify the operational RBS rocketback flight envelope. Various approahces of plotting and describing the potential RBS flight envelope were presented. Also, discussed were trades on the operational RBS vehicle design, trajectory approach, and mission scenarios that have different impacts on the flight envelope.

The rocketback flight envelope presented still needs further definition by incorporating analysis from some of the trades mentioned here and perhaps others that weren't discussed. More visualization can be done by using a parametric approach to these trades so a designer can understand which parameters drives the rocketback trajectory towards different parts of the envelope. Projected operational needs also need to be incorporated so regions of the flight envelope can be prioritized to help guide development efforts. Overall, the authors' intention with this document is to provide a starting point for developing the rocketback trajectory as a means for enabling the next generation of responsive and cost effective launch.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ACRONYM	DESCRIPTION
α	Angle of Attack
CCAFS	Cape Canaveral Air Force Station
C_{Lmax}	Maximum Lift Coefficient
deg	degrees
delta-V	Change in Velocity
fps	Feet per second
ft	foot
IOC	Initial Operating Capability
Isp	Specific Impulse (sec)
lbs	Pounds
LCC	Life Cycle Cost
LEO	Low Earth Orbit
LOX	Liquid Oxygen
OTIS	Optimal Trajectories by Implicit Simulation
POST	Program to Optimize Simulated Trajectories
psf	Pounds per square foot
RBS	Reusable Booster System
RCS	Reaction Control System
RECO	Rocketback Engine Cut-Off
RTLS	Return to Launch Site
T/W	Thrust to Weight Ratio
V-n	V = Velocity n = loads in g's